INTEGRATION OF HELIOCLIM-1 DATABASE INTO PV-GIS TO ESTIMATE SOLAR ELECTRICITY POTENTIAL IN AFRICA

T.A. Huld[1], M. Šúri[1], E.D. Dunlop[1], M. Albuisson[2], L. Wald[2]
[1] European Commission, DG JRC, Renewable Energies Unit, T.P. 450, via E. Fermi 1, Ispra, (VA) 21020 Italy,
[2] Ecole des Mines de Paris, Centre Energétique et Procédés, BP 207, 06904 Sophia Antipolis Cedex, France,
email: ewan.dunlop@cec.eu.int, thomas.huld@jrc.it, marcel.suri@jrc.it,
michel.albuisson@ensmp.fr, lucien.wald@ensmp.fr

ABSTRACT: we present a method for computing high resolution database of global horizontal irradiation for Africa and the Mediterranean Basin. Following this, we analyse the geographical and time variability of the solar energy potential for electricity applications. The primary solar radiation data were previously computed from Meteosat satellite images by the Heliosat-2 method and stored in the HelioClim-1 database. From this database, the long term monthly and yearly averages of global irradiation on horizontal plane (period 1985-2004) were derived. Using the PV-GIS method, based on a clear-sky model, interpolation of the clear-sky index and terrain shadowing, the original spatial resolution of HelioClim-1 database (15’) was enhanced to 2 km. Using daily global irradiation from the enhanced PV-GIS database we estimated the electricity generation from a typical solar home system. Assuming a 100 W_p installation with a battery and battery charger, together with a performance ratio of 0.75, the power production ranges from about 0.3 to 0.6 kWh per day in most locations in Africa.
Keywords: HelioClim database, Heliosat method, Geographical Information System, Solar Radiation Model, PV Power Generation

1 INTRODUCTION

Photovoltaics (PV) holds great promise for the poorest of the developing countries where the solar resource is abundant and electricity grid penetration is low, as is generally the case in Africa. Compared to other electricity generation systems, and to developing extended electricity grid within countries, small-scale off-grid applications are already now cost-effective. However, the proper configuration of a PV system depends on the knowledge of solar resource, which, although generally high, shows considerable geographical and seasonal variation within the continent.

The number of stations within the existing radiometric ground network in Africa is small and their uneven spatial allocation cannot provide detailed structure of the solar resource. Therefore, the only data available for energy resource assessment are those from satellites.

At the Ecole des Mines de Paris, the Heliosat-2 method was developed to convert Meteosat satellite images into solar radiation data. By means of the Heliosat-2 method and images from the Meteosat Prime satellite, the database HelioClim-1 of global horizontal irradiation has been created. The basic data can be accessed through the SoDa intelligent online service.

The PV-GIS approach makes it possible to enhance the spatial resolution of the solar radiation data. It also provides a web interface that links spatial databases with maps and interactive tools for data query, display and for the assessment of solar electricity generation.

Based on previous works, we present a method for enhancing the spatial resolution of the HelioClim-1 solar radiation database using the PV-GIS approach. The new 2-km grid database for Africa and the Mediterranean Basin is analysed in the second stage, with focus to regional variability and dynamics of the solar resource potential for electricity applications.

2 METHODS

2.1 HelioClim-1 database

HelioClim-1 is a unique and homogenized database created from Meteosat satellite images by the application of the Heliosat-2 method [1,2]. The primary database contains only the cloud index and a set of parameters that are processed by a dedicated software to calculate daily global irradiation on horizontal plane from 1985 onwards. The database and software are accessible through the SoDa intelligent web system [3]. The SoDa interface allows retrieving daily values or monthly averages for requested location and year. For the purpose of this work, an automatic direct access was enabled using PHP scripts.

The spatial extent of the HelioClim-1 database corresponds to the field of view of the Meteosat Prime disc (the satellite being centred at latitude 0° and longitude 0°). Due to the lower reliability of results at low solar elevation angles (less than 12 degrees) the restriction of the software does not allow calculating irradiation data from extreme North and South latitudes in winter months. The primary spatial resolution of the HelioClim-1 database is about 15 arc minute, i.e. a grid cell close to the equator represents an area of about 30x30 km².

The accuracy of the HelioClim-1 has been assessed by comparisons with measurements of the WMO radiometric network in Europe (55 sites) and Africa (35 sites) for the period 1994-1997. The RMS error of monthly averages of daily irradiation is 600 Wh/m^2, and bias is 24 Wh/m^2.

2.1 Developing the PV-GIS database for Africa

In previous works [4,5] we have described a methodology for calculating higher resolution solar radiation database using the solar radiation model *r.sun* and spline interpolation method *s.surf.rst*, both implemented in the geographical information system (GIS) GRASS [6].

The algorithm of the clear-sky model *r.sun* is implemented based on the equations published in the European Solar Radiation Atlas [7]. It estimates beam, diffuse and reflected components of the clear-sky (i.e.

cloudless sky) global irradiance/irradiation on horizontal or inclined surfaces. The daily global irradiation for clear-sky H_{cd} is computed by the integration of irradiance values calculated with a time step of 15' over the day from sunrise to sunset. The two main input parameters to the *r.sun* model were the Linke atmospheric turbidity (original data resolution of 5 arc minute [8]) and the digital elevation model (DEM) derived from USGS GTOPO30 data (original data resolution of 30 arc second [9]). For each time step during the day, the computation accounts for shadowing by local terrain features, calculated from the DEM.

The spatial resolution of the enhanced database for Africa and the Mediterranean Basin was set to 2 km. The high resolution database was calculated in the following steps:

1. Long term (1985-2004) monthly averages of daily global irradiation on horizontal plane, H_m, were calculated from HelioClim-1 data. Using the *r.sun* model and input parameters of Linke turbidity and DEM with the same resolution as the primary data (15') the monthly averages of the clear-sky irradiation H_{cm} were calculated for the same grid cell. Then, the monthly averages of clear-sky index k_{cm} were calculated:

$$k_{cm} = H_m / H_{cm} \quad (1)$$

The k_{cm} parameter quantifies the attenuation of clear-sky global irradiation by cloud cover. At that point, we had 12 sets of k_{cm}, one per month.

2. The sets of k_{cm} were re-projected from longitude/latitude database to the high resolution database (Lambert azimuthal equal-area projection) and re-interpolated using *s.surf.rst* at a resolution of 2 km. This produced 12 new sets of clear-sky indices, k_{cm2}. A similar operation was performed to produce a map of Linke turbidity factor at a resolution of 2 km.

3. For each month, a high-resolution clear-sky global irradiation H_{hc} was computed by the means of *r.sun* and high resolution Linke turbidity and DEM data. Monthly averages of daily global irradiation on horizontal plane, H_{rm}, were calculated in the 2-km grid resolution from the k_{cm2} indices (step 2) and H_{hc}:

$$H_{rm} = H_{hc}\, k_{cm2} \quad (2)$$

The resulting GIS database has a grid resolution of 2 km and consists of 12 monthly averages and the yearly average of daily sums of global irradiation on horizontal plane, expressed in Wh m^{-2}. The database represents the period 1985-2004 and the values account for terrain shadowing by mountains.

The data and maps with enhanced 2-km resolution are available online via an interactive web tool [10].

2.3 Solar electricity assessment

From these monthly averages of radiation, we have estimated the electricity generated by a typical solar home system. We have assumed a horizontally mounted installation with nominal peak power[1] P_k =100 W$_p$, with a battery and battery charger, together with a performance ratio r_p of 0.75 The electrical energy, E (in Wh), generated daily by such a system is estimated as follows:

$$E = P_k\, r_p\, H_{rm} \quad (3).$$

[1] Nominal peak power is the power output at Standard Test Conditions with in-plane irradiance of 1000Wm^{-2} at module temperature of 25°C.

3 RESULTS

3.1 Solar radiation database

The high resolution database better reflects the spatial variability of the solar energy resource, where systematic latitudinal structure is modulated by patterns of atmospheric turbidity, cloud structures, and terrain elevation (including shadowing). The increase of detail in the enhanced database (compared to the original one) is mostly determined by the high resolution DEM as can be seen in the Figure 1.

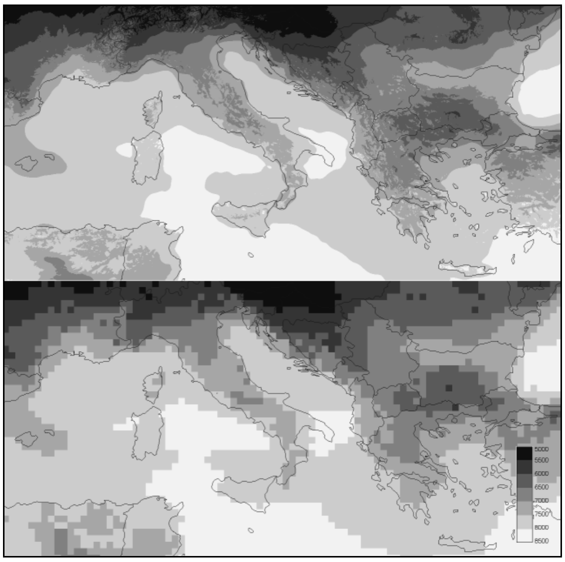

Figure 1: Monthly average of daily global irradiation on horizontal plane in July (Wh m^{-2}); an excerpt from the Mediterranean Basin. Bottom: the original HelioClim-1 data with spatial grid resolution of 15', top: the enhanced PV-GIS database with spatial resolution of 2 km.

The maps show significant geographical and seasonal variation of global irradiation over the African continent, with values varying by almost a factor of 2 (Figure 2). These variations do not correlate with the geographical latitude; they are determined by regional climatic features [11]. In dry regions, such as the Sahara and Kalahari deserts, the irradiation is very high, while on contrary, in the tropical rainforest regions (such as is the Congo River Basin) it is much lower, especially near the Western coast.

3.2 Potential for solar electricity generation

The enhanced database and maps provide more detailed information on solar radiation for any location in the region. The GIS and internet tools provide integrated statistics that is needed for the assessments of PV systems.

Assuming a small, 100 Wp stand-alone installation with a battery and battery charger, together with a performance ratio of 0.75, the power production ranges from about 300 to 600 Wh per day in most locations in Africa, except in winter season in the extreme North and South of the continent. This energy is sufficient to drive 3 energy-efficient lights for 6 hours per day, or 3 energy efficient lights for 4 hours plus a radio, or a pump to deliver 1200 litres of water from a depth of 10 meters.

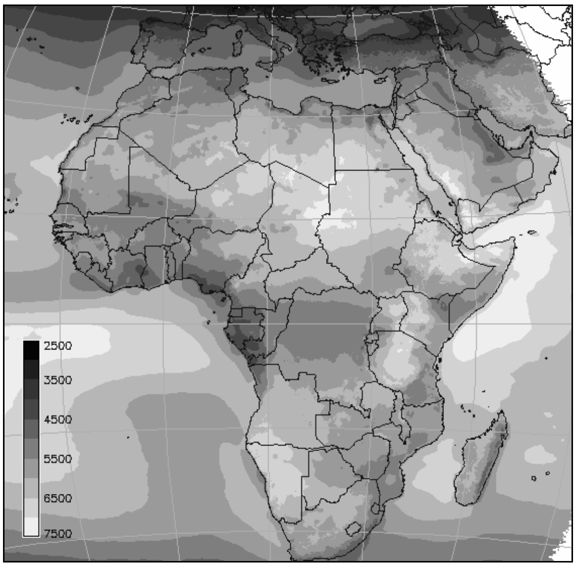

Figure 2: Yearly average of daily global irradiation on a horizontal plane, for the period 1985-2004 (in Wh m^{-2}).

The output variation during the year is location-dependent. In regions with dry climate, the energy produced is generally higher but with higher seasonal variation, especially in the northernmost and southernmost latitudes. On the other hand, in humid equatorial climates, such as the Congo River Basin, the level of production is much lower with low seasonal variation. There is not enough space in this paper for detailed climatic characterisation of the continent and comparison with the previous works (e.g. [11]). However some applications of both HelioClim-1 and enhanced solar radiation databases are demonstrated on an example of two cities – Kinshasa (Dem. Rep. of Congo) and Asmara (Eritrea).

From monthly averages of daily global irradiation, we have estimated the potential electricity output from PV systems (Figure 3). For stand-alone PV systems consideration of the variation during the year is important to avoid periods of insufficient power production. Similarly, for a proper PV configuration a probability distribution of daily irradiation is needed. This can be derived from the original HelioClim-1 database as it stores daily data (Figure 4). The results show clearly the divergence between different sites. In Kinshasa very high irradiances are rare and the distribution of daily irradiation values is rather broad. In contrast, in Asmara it is much more likely that the daily irradiation will be near the maximum (clear-sky) irradiation.

Availability of daily irradiation data for a given location makes it possible to optimize different PV system components. Assuming certain daily energy consumption, it is possible to estimate the optimum peak power of the solar module and the size for the battery.

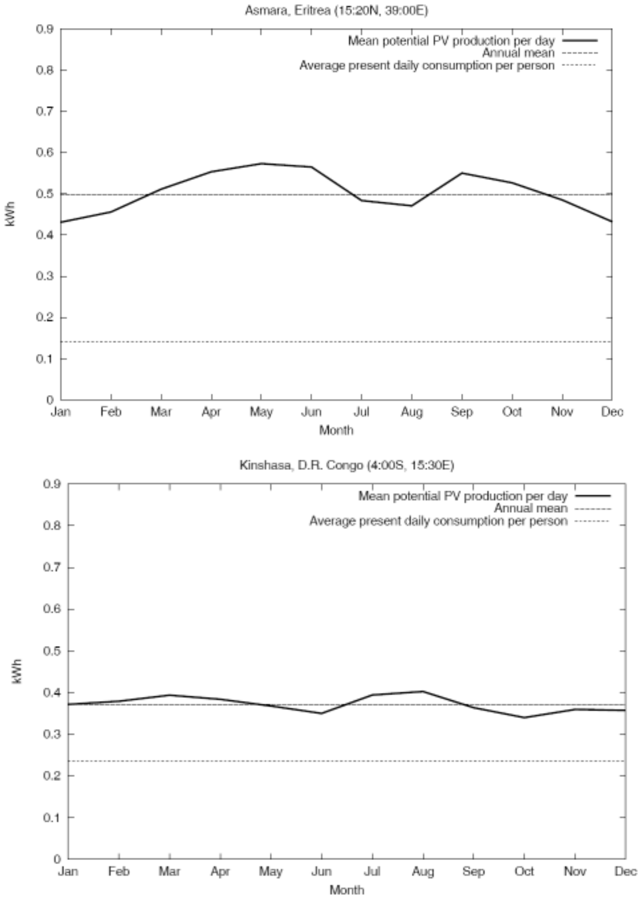

Figure 3: Seasonal variation of the daily PV electricity generation from a 100 W_p system in Asmara and Kinshasa (red line). The graphs also show the annual mean daily generation (green line) and this is compared with the average daily electricity consumption per capita in the respective countries (blue line, source [12]).

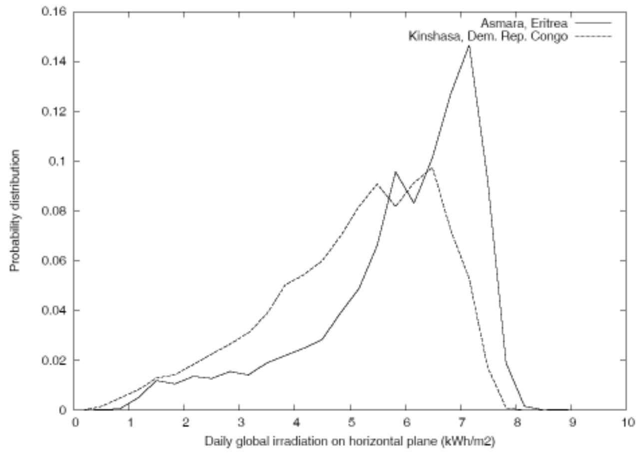

Figure 4: Average probability distribution of daily irradiation (kWh m^{-2}) within a year in Asmara and Kinshasa. The data represent the period 1985-2004.

For optimization of size of system components, the daily irradiation data can be used for a location to simulate the battery load status day by day for a given PV system size. In the following example for the Asmara location it is assumed that the PV system will charge the battery during the day, and that the power will be consumed after sunset. Then it is calculated how often power will run out depending on the desired consumption (Figure 5). The percentage of days where a user runs out of power depends strongly on battery size up to a certain point. Beyond this point, the limiting factor is the size of the system, and an increase of the battery size will have little beneficial effect. In our case the optimum battery size is equal to the size of the consumption up to about 550 Wh per day, which is about 10% higher than the yearly average energy output from the system.

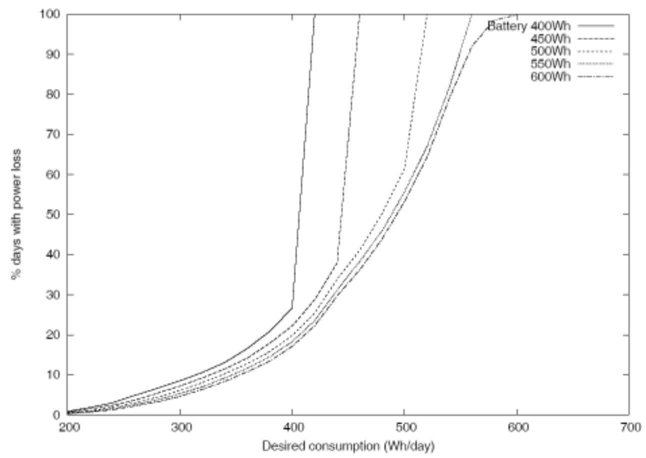

Figure 5: Performance of a 100 W_p system in Asmara, depending on desired power consumption and battery size, indicated by the percentage of days where power runs out. Calculation is based on daily irradiation data for the period 1985-2004.

4 DISCUSSION

We have compared the electricity output from a 100 W_p PV system with the average per capita electricity consumption for a number of African countries [12]. Already the first analyses demonstrate that small stand-alone PV systems can meet electricity demands of most African families. In countries with very low electricity consumption, such as Chad or Burkina Faso, a 100 W_p configuration provides electricity to a family at a level that is above the national average.

5 CONCLUSIONS

The solar radiation data derived from satellite images and processed in GIS open new horizons to the deeper comprehension of spatial and time dimensions of solar energy resource and its exploitation for satisfying energy needs of African countries.

Enhancement of the spatial dimension is considered as a first step to further developments that are on the way. Calculation of diffuse/global ratio will provide for estimations of output energy from PV systems with inclined modules. Synthesized statistics will provide means for better optimisation of stand-alone systems and estimation of irradiation profiles during a year. The database and web interface system can be also adapted to assist in monitoring of the existing PV installations.

An important component of the work is to provide user-friendly access to the basic radiation data and assessment tools for any chosen location to professionals, decision-makers as well as to the general public. To this end the experience from the previously developed web interface to the PV-GIS database for Europe has been used to prepare a similar prototype version for Africa and the Mediterranean Basin [10].

REFERENCES

[1] Rigollier C., Lefèvre M., Wald L., Solar Energy, 77 (2004) 159.

[2] Lefèvre M., Rigollier C., Cros S., Wald L., Proceedings of 22nd EARSeL Annual Symposium, Prague, Czech Republic (2002) 223, http://www.helioclim.org/.

[3] Wald L., Proceedings of the European Geophysical Society Meeting, XXV General Assembly, Nice, France (2000) http://www.soda-is.com/.

[4] Šúri M., Hofierka J., Transactions in GIS, 8 (2004) 175.

[5] Šúri M., Huld T.A., Dunlop E.D., International Journal of Sustainable Energy, 24 (2005) 55.

[6] Neteler M., Mitasova H., Open Source GIS: A GRASS GIS Approach, Kluwer Academic Publishers, Boston (2002).

[7] Scharmer K., Greif J. (eds), The European Solar Radiation Atlas. Vol. 2: Database and Exploitation Software, Paris, Les Presses de l'École des Mines (2000).

[8] Remund J., Wald L., Lefèvre M., Ranchin T., Page J., Proc. ISES Solar World Congress, Göteborg, Sweden (2003).

[9] Global 30 Arc-Second Elevation Data Set GTOPO30, online archive, http://edc.usgs.gov/

[10] PV-GIS web site: http://re.jrc.cec.eu.int/pvgis/pv/.

[11] Diabaté L., Blanc Ph., Wald L., Solar Energy, 76 (2004) 733.

[12] Key World Energy Statistics, 2004 Edition, International Energy Agency, Paris, France (2004) http://www.iea.org/bookshop/add.aspx?id=144.